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PHYSICAL PICTURE OF THE FORMATION OF AN
ARTIFICIAL RADIATION BELT BY THE AMERICAN
HIGH-ALTITUDE THERMONUCLEAR BURST OF 9 JULY 1962

by

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by

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Summary

Direct observations by Kosmos-5 and other satellite sources
indicate that the final radius of the plasma cloud accompanying
the American high-altitude burst of 9 July 1962 did not exceed
600 km. This is less than the final radius for a plasma cloud
expanding in a vacuum, which indicates considerable dissipation
of energy. Particle ejection beyond the plasma cloud is assumed
to be the reason for this discrepancy and three mechanisms are
proposed to explain the ejection: 1) diamagnetic ejection of
plasma blobs due to instability at the interface between plasma
and field; 2) free separation in the magnetosphere of fission
fragments neutralized in the beginning stages of cloud expansion,
i.e., before the stage of "inertial separation"; 3) free separation in the magnetosphere of fragments neutralized by charge
exchange between ions in the plasma cloud and neutral particles
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PHYSICAL PICTURE OF THE FORMATION OF AN ARTIFICIAL RADIATION BELT BY THE AMERICAN HIGH-ALTITUDE THERMONUCLEAR BURST OF 9 JULY 1962*

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Yu. I. Gal'perin

As has already been reported [1,2], instruments aboard the Satellite "KOSMOS-5" intended for the measurement of soft corpuscular radiation in the upper atmosphere recorded a burst of γ-radiation far beyond the limits of direct visibility of the burst region. If the altitude of the screening layer δ for γ-radiation is taken into account, radius r_{min} of a spherical cloud of plasma centered at a point with coordinates ϕ_0, λ_0, h_0, whose boundary would be tangent to the lower limits of the zone of direct visibility from the satellite (with coordinates ϕ_c, λ_c, h_c), can be found from the formula

$$r_{min} = -(R_3 + h_0)\cos(0_0 - \mu) + (R_2 + \delta), \tag{1}$$

$$\left.\begin{array}{l} \cos 0_0 = \sin \phi_0 \sin \phi_c + \cos \phi_0 \cos \phi_c \cos(\lambda_c - \lambda_0) \\[2mm] \cos \mu = \dfrac{R_3 - \delta}{R_3 + h_c}; \quad R_3 \text{ — radius of the Earth} \end{array}\right\} \tag{2}$$

With the satellite coordinates given in[1], the burst point h_0 = 400 km above Johnston Island[3], and using the calculated value δ = 64 km, we obtain $r_{min} \approx 770$ km. It is very important in the interpretation of the γ-radiation burst whether the radius of the expanding plasma cloud formed by the burst exceeded or did not exceed the magnitude of r_{min}; i.e., whether the cloud penetrated into the zone of direct visibility. Let us consider the experimental data on the diameter of a cloud of plasma in the geomagnetic field. First of all, such data can be obtained from observations of the artificial aurorae that accompanied the burst.

Photometric observations of the luminosity of the aurora in the near-equatorial regions of the southern hemisphere [3] showed that

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intense luminosity was created in a belt $\pm 5^{\circ}$ wide in longitude along the geomagnetic meridian of Johnston Island immediately after the explosion. This luminosity could have resulted from direct excitation by particles from the plasma cloud which were absorbed in the atmosphere at the conjugate point. The luminosity could also have originated from a number of other causes: as a consequence of excitation by energetic photo-electrons formed beyond the limits of the plasma cloud by the action of short-wavelength radiation from the burst; or as a result of a discharge in the conjugate region of the ionosphere under the action of the electric field originating in the tube of force containing the expanding plasma cloud and transmitted along the field to the conjugate point as a consequence of the high electrical conductivity of the upper atmosphere along the field, and the like. However, the diameter of the region of luminosity obtained with all mechanisms is not less than the cloud diameter, although a very interesting fine-structure, i.e. thin rays, reminiscent of the natural polar aurora, was also observed inside the aurora. From this it follows that the radius of the plasma cloud in the horizontal direction along an east-west line did not exceed ~ 600 km.

Most important is determination of the limits of expansion of the cloud along the L-shells of charged particles' motion. Such data were obtained from measurements on the satellites "TRAAC" and "ARIEL" [3,4] by analyzing the intensity distribution in the "second" artificial belt of relativistic electrons which were injected by fission fragments remaining in the upper atmosphere of the burst region after dispersion of the plasma cloud. Inasmuch as the lower limit of the artificial belt $(h_{min} \sim 200$ km over Johnston Island) passed only at an altitude of ~ 1000 km, the lower-lying regions of space can be populated only by"fresh" β-decays [Ref. 3, p. 64]. This permits data to be obtained on the distribution of fission fragments in the first to second days after the burst. It was found that the intensity of the "secondary" artificial belt fell off sharply for $L > 1.18$, so that a deep intensity minimum was observed between the

secondary and main belts [Refs. 3,4]. These results agree with the measurements on "KOSMOS-5". The shell L = 1.18 passes over Johnston Island at an altitude of about 700 km. Since it is difficult to expect an appreciable drift of these particles due to the circulation of the upper atmosphere in the course of the first 24 hours, the data presented here indicate that the radius of the tube of force containing the main portion of the fission fragments did not exceed ~ 300 km over Johnston Island and the maximum L-value reached was $L \approx 1.18$ [4].

Finally, a photograph was published in Ref. 5 of the lunimous region in the upper atmosphere taken in the 5777 $\overset{o}{A}$ hydrogen line over Johnston Island 3 minutes after the burst, at a distance of ~ 1000 km, and the disposition of the magnetic lines of force and of the burst point is indicated. The luminosity within this interval of time must have arisen principally from β-decay of the radioactive products of the burst, and consequently, the location of the region of luminosity reflected the dispersion of the fission products in the atmosphere. From the photograph it is evident that the luminosity extended only within a tube of force of radius less than 400 km near the burst point. These direct data, therefore, are in good agreement with the deductions given above, which were obtained from analysis of the measurements of the "secondary" artificial belt.

Thus, direct observations show that the final radius r_k of the plasma cloud did not exceed 600 km, and possibly it was even smaller. The maximum radius attained by the plasma cloud is less than the final radius R_k of the expansion of the cloud of plasma in a vacuum [Ref. 6], which indicates a significant dissipation of the energy of the plasma expanding in the ionosphere in the vicinity of the F-layer maximum. The indicated value $r_k < r_{min}$ and, consequently, the cloud is located entirely below the horizon for the satellite "KOSMOS-5". (Precisely for this reason, the term "γ-shine" was proposed in Ref. 1 as a qualitative metaphor to designate the detected burst of γ-radiation).
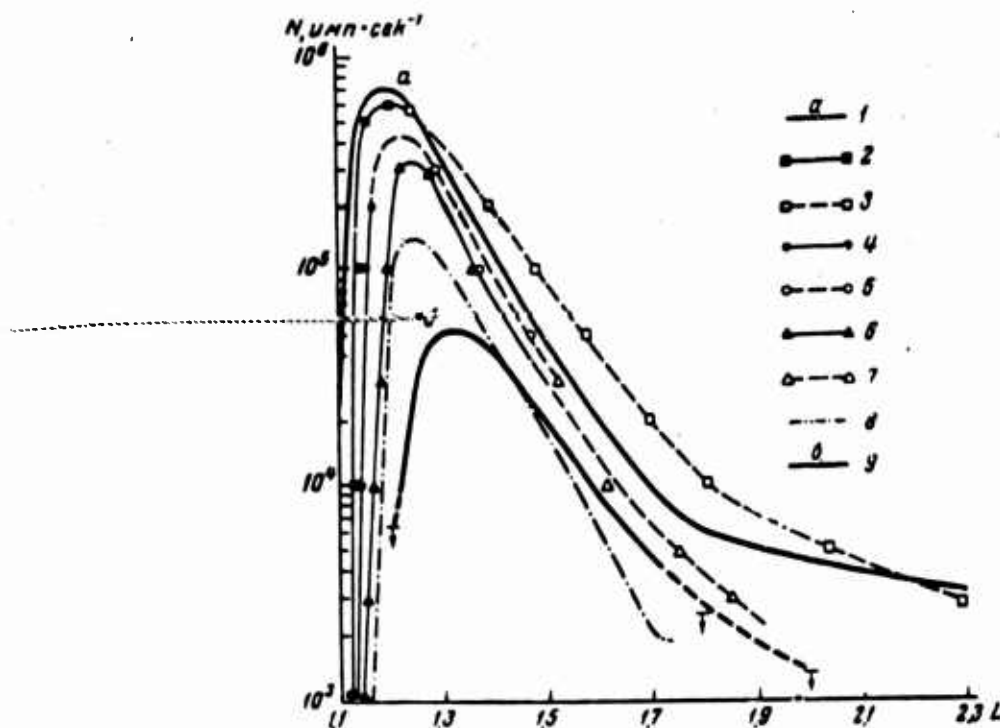
Figure 1. Distribution over L of the counting rate N (pulses/sec) of the Geiger counter on KOSMOS-5 in the equatorial plane. Measurements and model (see text) and the EXPLORER-15 and ELECTRON-1 measurements are normalized to the same intensity of the fission β-spectrum.

I. - From KOSMOS-5 data (1962): 1-measured ($L \lesssim 1.25$) and model ($L \gtrsim 1.25$), 9 July; 2 and 3- measurements and model, resp., 10 July; 4 and 5- measurements and model, 17 and 19 July, resp.; 6 and 7- measurements and model, 12 August and 16 Oct., resp.

II. - From EXPLORER-15 data: 8 - E > 4.5 Mev, 1 Jan. 1963.

III. _ From ELEKTRON-1 data: 9 - E > 1.1 Mev, Feb. 1964.

Nonetheless, fission fragments undoubtedly penetrated to high altitudes (and high L-values), inasmuch as the radiation belt extended at least up to L ~ 3.5 (according to data from KOSMOS-5, Ref. 2) and up to at least L ~ 6.5 (according to data from ARIEL, Ref. 4). In Fig. 1 are given the results of the construction of model distributions of the counting rate of the KOSMOS-5 counter, In their lower portions they coincide with the values measured on the KOSMOS-5 and were extrapolated to the equatorial plane on the following basis: a) intensity measurements in the artificial belt during 1964 from the satellites ELEKTRON-1 and ELEKTRON-3, and b) measurements of the rate of decay of intensity (lifetime) by the satellites KOSMOS-5, and also INJUN-1 and INJUN-3 [Ref. 7], EXPLORER-15 and RELAY-1 [Ref. 8], ELEKTRON 1 and ELEKTRON-3

[Ref. 9] and calculations [Ref. 3, p. 98; Ref. 10]. In this same figure, for comparison, are shown the results of the measurement of hard electrons (E $\gtrsim$ 4.5 Mev) on the EXPLORER-15 [Ref. 8]. This is a lower estimate, since it was assumed that the particle concentration in the tube of force above about h_{min} = 500 km was constant, i.e. the distribution was isotropic.

As can be shown, the volume U(L)dL of a radiation belt of thickness dL above some h_{min} is

$$U(L)dL = \left(4/3\pi R_3^3\right) \cdot \frac{3}{35} \cdot L \cdot \sqrt{\frac{l-1}{l}}\left(16 + \frac{8}{l} + \frac{6}{l^2} + \frac{5}{l^3}\right)dL,$$
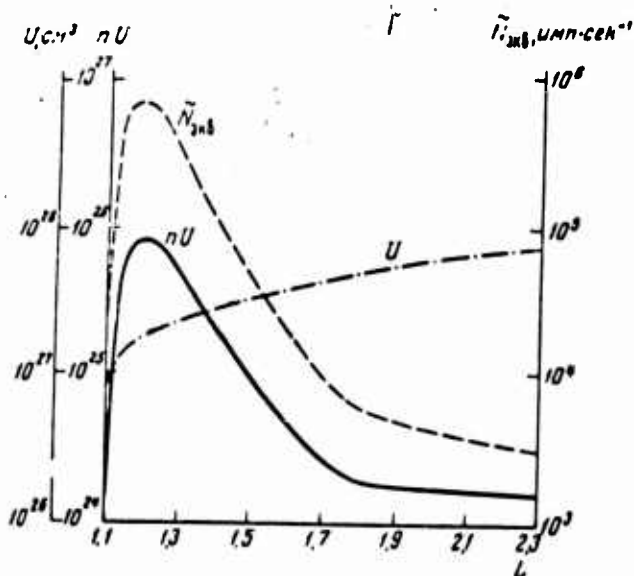
where

$$l = L \cdot \frac{R_3}{R_3 + h_{min}}.$$

(3)

Figure 2. The function U(L), and also the total number of electrons on the L-shell, n(L) U(L). The first model of the intensity distribution $\tilde{N}_{eq}$ in the equatorial plane is shown for comparison.

The plot of the function U(L) is given on Fig. 2 together with the model distribution of counting rate $\tilde{N}_{eq}$ for 9 July 1962. On Fig. 2 is also shown the toal content of trapped electrons in the belt (nU), with n = $\tilde{N}_{eq}$ × Kc, where $1/K$ is the counting efficiency to β-spectrum fission fragments (K = 2 × 10^3 particles × cm^{-2}/pulse and c is the velocity of light).* Integrating the quantity nU over L gives the total number of electrons injected into the belt.

As a result of integration, it was found that after about one hour after the burst there were about 1.5 × 10^{25} electrons in

*We ignore the possible softening of the fission electron spectrum with increasing L [Ref. 3, p. 7], since measurements by ELEKTRON-1 and ELEKTRON-2 [Ref. 9] showed that in this region there existed a very intense electron component of natural origin, which was not excluded in the results [Ref. 3, p. 8].

the artificial belt with energies greater than 20 Kev. An estimate shows that such a quantity of electrons in the belt required the decay at corresponding altitudes (above about 1200 km over Johnston Island, i.e., in the limits of direct visibility from KOSMOS-5) of the fragments of about 10^{25} fissions [Ref. 2] whereas during the burst about 2×10^{26} fissions [Ref. 3, p. 25] had evidently taken place.

An upper estimate of the time during which these fission fragments penetrated far from the confines of the plasma cloud can be obtained from the measurements of the burst of γ-radiation. The most important factor is that the products of exactly 10^{25} fissions were found [Ref. 2] within the zone of direct visibility from KOSMOS-5 only 3 seconds after the burst. The quantitative agreement of data on the number of injected fission fragments from measurements of the radiation belt and from measurements of the "γ-shine" leads to the conclusion that both these effects, the "γ-shine" and the radiation belt have the same source - the decay of a small portion of the radioactive fission fragments in the geomagnetic fieldbeyond the limits of the burst cloud. The particles may possibly be ejected beyond the limits of the cloud by the following mechanisms [Ref. 2] (Fig. 3).
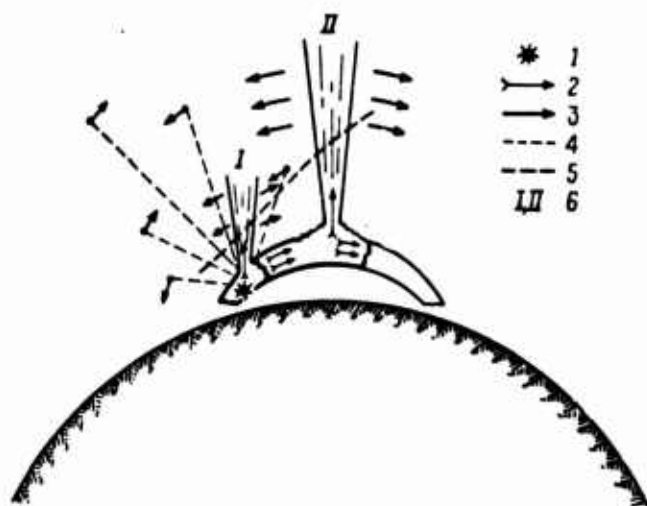

Fig. 3. Sechematic illustration of the diffusion of fission fragments in the upper atmosphere following the explosion.

1- Burst point; 2- plasma motion; 3- motion of trapped particles; 4- motion of neutral particles; 5- horizon line for KOSMOS-5; 6- eruptive ejection of plasma.

A. Diamagnetic ejection of blobs of plasma owing to instability at the plasma-field boundary. Actually, this boundary is convex toward the field and thus cannot be stable [Ref. 11]. As a consequence of the significant times of relaxation and expansion,

blobs of plasma will also be expelled toward the side of decreasing geomagnetic field, i.e. upward, much like the process of diamagnetic ejection of blobs of plasma in the solar chromosphere [Ref. 12].

B. Free dispersion in the magnetosphere of fission fragments neutralized in the initial stages of the expansion of the burst cloud, i.e. even before the state of "inertial dispersion". Such a mechanism was proposed in Ref. 4 to explain the observation by "ARIEL" of the burst of rapid counting about 20 seconds after the burst.

C. Free dispersion in the magnetosphere of fission fragments neutralized as a consequence of charge exchange between plasma cloud ions and neutral particles of the atmosphere. Since the number of neutral particles along the path of a fission fragment, and also the degree of ionization in the atmosphere after the burst, depend strongly on the angle between the velocity vector of the ion and the vertical (zenith angle z), the main part of these ions must have traveled in the vicinity of the horizontal plane with respect to the burst point and must have had some distribution of velocity v_o.

It must be considered that, on the average, β-decay of each of the two fission fragments occurs within 15 seconds, after which a fragment again becomes an ion and is "trapped" by the magnetic field. Some portion of the fragments is precipitated into the dense atmosphere and absorbed, which gives rise to an additional decrease in γ-radiation intensity after 10 to 20 seconds. On the other hand, owing to the approach of the satellite to the burst cloud and to the westward drift, toward the satellite, of the ionized fragments trapped after β-decay, some relative increase in γ-radiation intensity should take place in 1 to 2 minutes. However, during the course of the first ~ 200 seconds, neither of these effects is very significant. Figure 4 gives a comparison
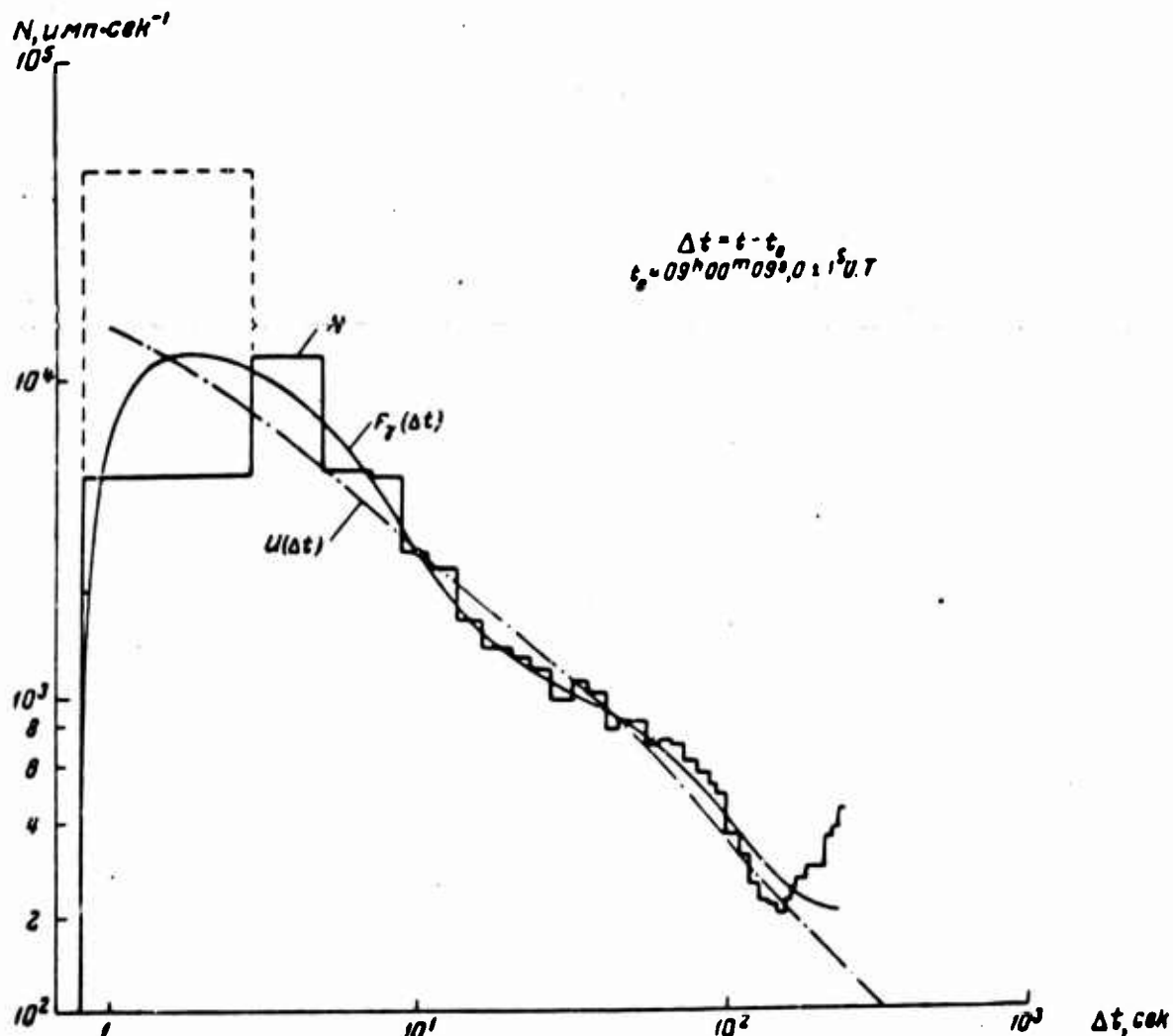
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Figure 4. Comparison of the calculated time trend of γ-radiation intensity for fission fragments with velocity $v_0 = 1000$ km sec^{-1} and the observed "γ-shine" 9 July 1962.

of the observed counting rate N of the counter aboard "KOSMOS-5" at the time of the "γ-shine" and the computed trend F_v (Δt) of the intensity of γ-radiation from fission fragments ejected at the moment $t_0 = 9$h 00 m 09.0 sec (UT) [Ref. 3] with uniform velocity $v_0 = 1000$ km sec^{-1} and with a distribution over Z proportional to B (z) - the Bemporad function, which is probably descriptive of charge-exchange particles. Taken into account were only the change in dilution coefficient due to expansion of the cloud (the first 15 seconds) and to the relative approach of the satellite (after 1 to 2 min); the departure of particles from the zone of direct visibility, the distribution of the particles with respect to v_0 and the effective scattering of γ-radiation in the atmosphere were neglected. Therefore, the agreement of final detail is in some respects fortuitous, although the qualitative character of the trend of γ-radiation intensity with time (proportionality u (Δt) after the first few seconds [Ref. 2]) is very

weakly dependent on v_o.

Some contribution to the observed intensity could also have been provided by fission fragments ejected by mechanisms A and B mentioned above. Auroral rays directed upward from the equatorial region of the tube of force of the burst, apparently connected with plasma outbursts, were in fact observed [Ref. 3].

In conclusion we express our gratitude to V. I. Krasovski, S. B. Pikel'ner, A. S. Strelkov and Yu. V. Kukushkin for their useful discussion of the results.

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